Physics 488, Fall 2019
Project #2: General Guidelines
Due Dec. 9 and 16

Overview. In project #2, we will shift to the mode of "numerical experiments" and explore simulations of gravitational dynamics. Each group will consider a set of related scenarios in which multiple bodies move under the influence of their mutual gravity. You will simulate the evolution of the system and then deliver your results in a professional-style paper and presentation. The project will account for 25% of the course grade, with 5 components listed below.

Gravitational dynamics. In each scenario, you will have a set of N bodies with masses m_i and positions $\vec{r}_i$. Strictly speaking, the dynamics are governed by the system of equations

$$\frac{d^2\vec{r}_i}{dt^2} = \sum_{j \neq i} \frac{Gm_j}{|\vec{r}_j - \vec{r}_i|^3} (\vec{r}_j - \vec{r}_i)$$

The acceleration diverges when two bodies approach one another, which can lead to numerical problems. One solution is to "soften" the force and write (see Merritt, 1996, AJ, 111, 2462)

$$\frac{d^2\vec{r}_i}{dt^2} = \sum_{j} \frac{Gm_j}{(\epsilon^2 + |\vec{r}_j - \vec{r}_i|^2)^{3/2}} (\vec{r}_j - \vec{r}_i) \tag{1}$$

where ϵ is the "softening length." Now the right-hand side vanishes when $\vec{r}_j \to \vec{r}_i$, which means the sum can run over all indices (i.e., we no longer have to exclude $j = i$). You will need to write code to solve the system of differential equations. I have several (strong) recommendations:

- You should try to avoid `for` loops and instead use vectorized calculations as much as possible. You may want to look back at `CalcDiff()` in the week 2 practical.
- You should work out the energy that corresponds to eq. (1) and check energy conservation.
- You should plan to check how much your results depend on ϵ.
- Try to write code that can handle an arbitrary N, and test it on the 2-body problem.

Python notebook for the full analysis (5 pts). Your final notebook should contain your complete analysis, including appropriate validation steps. Please document your code, label your plots, and use markdown cells to add explanatory comments to the notebook. You will submit a single python notebook for the group.

Python notebooks for individual sub-analyses (5 pts). You should identify a distinct part of the overall analysis for each member of the group. There can be some block of code in common, but each person should pose a unique question and present a custom analysis to answer that question. I will be happy to discuss possibilities as you start working on your project. Each person will submit the python notebook from their individual analysis.

Final paper (5 pts). The final paper should be created in LaTeX and follow the structure of an astrophysics research paper. In particular, the paper should explain the scientific context and question to be answered, describe the computational methods (including appropriate validation), present the results (using figures and/or tables as appropriate), discuss the implications, and include appropriate references. In the concluding discussion, please comment on how the methods used in contemporary research represent extensions of the methods you used. The paper should be written collaboratively (see below) and include all group members as coauthors. If appropriate, it can also include an acknowledgements section giving credit for conversations that proved helpful and/or resources that were used in the project.

Presentation (5 pts). Each group will give a 12-minute presentation in class on Dec. 9. The presentation should include the same basic content as the paper, although it does not necessarily have to have exactly the same structure. Your group can decide how to handle the delivery; it is fine to choose one person to give the presentation (as long as the overall effort in the project is equitable; see below). The presentation should be submitted as a Powerpoint, Keynote, or PDF file, or a Google slides document.

Individual reflection (5 pts). I will ask each of you to write a (brief) reflection on your experience with the project. What aspect did you find most interesting? What was the biggest challenge? How did material from class prepare you for the project, and are there things you wish you had learned first? How has this project helped you understand astrophysics research? What was your individual contribution to the group's work? There is no specific page requirement or limit, but I envision something around one page single-spaced.

A note about collaboration. The vast majority of astrophysics research is collaborative, with varying levels of contribution. In this case, the division of labor should be *equitable* but it does not necessarily to have be *equal*. For example, everyone should contribute to the analysis (at minimum through the individual sub-analyses), but you might have one person who is principally responsible for writing the overall Python notebook. Everyone should contribute to the paper and presentation, but one person might focus more on slides while another focuses more on LaTeX, or one person might focus more on figures while another focuses more on text. As noted above, the individual reflection should explain how you contributed to the overall effort. (I will take note of any inconsistencies between those descriptions.)

Products. To summarize, here are the products and deadlines:

- Dec. 9 at 9am: one presentation file for the group
- Dec. 9 at noon: one python notebook for the group
- Dec. 9 at noon: individual analysis from each member of the group
- Dec. 16 at noon: one final paper for the group
- Dec. 16 at noon: individual reflection from each member of the group